

# Constraining decaying dark matter with neutron stars

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We propose that the existing population of neutron stars in the galaxy can help constrain the nature of decaying dark matter. The amount of decaying dark matter, accumulated in the central regions in neutron stars and the energy deposition rate from decays, may set a limit on the neutron star survival rate against transitions to more compact stars and, correspondingly, on the dark matter particle decay time,  $\tau_\chi$ . We find that for lifetimes  $\tau_\chi \lesssim 6.3 \times 10^{15}$  s, we can exclude particle masses  $(m_\chi/\text{TeV}) \gtrsim 50$  or  $(m_\chi/\text{TeV}) \gtrsim 8 \times 10^2$  in the bosonic and fermionic cases, respectively. In addition, we also compare our findings with the present status of allowed phase space regions using kinematical variables for decaying dark matter, obtaining complementary results.

Disentangling the nature of dark matter (DM) is one of the greatest current challenges in physics. Whether it is realized through a stable or a decaying particle remains unknown to date. There is a vast literature with many well-motivated particle physics models containing unstable, long-lived, DM particle candidates, see e.g. [1] for a review. From the phenomenological side, there are results that constrain possible DM decay time-scales,  $\tau_\chi$ , from cosmic microwave background (CMB) anisotropies [2], galaxy cluster abundances [3], DM halo simulations [4], and the observed excess in the cosmic electron/positron flux [5]. In most of these works, it is usually assumed that the decay daughter particles are (nearly) massless although a more generic situation with arbitrary non-zero masses,  $m_D$ , may well happen [6]. The spread of the current bounds on the DM lifetime  $\tau_\chi$  or, equivalently, on the DM decay rate  $\Gamma_\chi = 1/\tau_\chi$  is large. In light of the Pamela [7] and Fermi LAT [8] data, these can be interpreted in a scenario where a decaying  $\chi$ -particle has a lifetime  $\tau_{e^+e^-} \sim 10^{26}$  s, for DM masses  $m_\chi \gtrsim 300$  GeV and well into the TeV range [9] (we use  $c = 1$ ). Such lifetimes may appear in the context of supersymmetric grand unification theories through operators with mass dimension 6,  $\tau_D^{\text{GUT}} \sim 10^{27} \text{ s} \left( \frac{\text{TeV}}{m_\chi} \right) \left( \frac{M_{\text{GUT}}}{2 \cdot 10^{16} \text{ GeV}} \right)^5$ . On the other hand, CMB data provide a constraint  $\Gamma_\chi^{-1} \gtrsim 30 \text{ Gyr}$  for massless daughter particles while for sufficiently heavy ones the decay time  $m_D \lesssim m_\chi$  remains unrestricted [6]. This agrees with analysis on the stability of DM halos based on kick velocities of particles in the decay [4] and combined constraints based on Lyman- $\alpha$  forest, Planck and WMAP data [10, 11].

In this work we consider a scenario where weakly interacting (WIMPy) scalar bosonic or fermionic metastable DM is gravitationally accreted on a neutron star (NS). These objects are compact, with typical radius  $R \simeq 10$  km and mass  $M \simeq 1.5 M_\odot$ . In a simplified description, they are believed to have a central core region, which constitutes most of the star, where mass densities are supranuclear. Although there is a rich phenomenology on the possible internal core composition we consider it here as composed of nucleon fluid, with mass densities  $\rho_n \sim [1 - 10]\rho_0$  ( $\rho_0 \simeq 2.4 \times 10^{14} \text{ g/cm}^3$ ). Under these conditions NSs are efficient DM accretors as they can effectively capture an incoming  $\chi$ -particle passing through the star. In order to see this, let us recall that a WIMPy DM particle may have a mean free path much smaller than the typical NS radius  $\lambda_\chi \simeq \frac{1}{\sigma_{\chi n} n_n}$  where  $\sigma_{\chi n}$  is the  $\chi$ -nucleon elastic scattering cross-section and  $n_n = \rho_n/m_n$  with  $m_n$  the nucleon mass. Compilation of the latest results in direct detection searches [12] allows analysis to the level of  $\sigma_{\chi n} \simeq 10^{(-44 \div -42)} \text{ cm}^2$  in the  $m_\chi \sim (10 - 10^4) \text{ GeV}$  range. Inside the NS each DM particle will scatter a number of times given by

$$R/\lambda_\chi \simeq 8.5 \left( \frac{R}{10 \text{ km}} \right) \left( \frac{\sigma_{\chi n}}{10^{-44} \text{ cm}^2} \right) \left( \frac{\rho_n}{5\rho_0} \right). \quad (1)$$

However, accretion of DM will proceed not only during the NS lifetime, but also in the previous late stages of the progenitor star where the dense nuclear ash central core allows the build-up of a  $\chi$ -distribution,  $n_\chi(r)$ , over time. In previous work, we have considered the effect of a self-annihilating DM particle on the internal NS dynamics

[13–16] but here we will focus on the possibility that the only process depleting DM is decay. We will assume that DM has remained in the universe with an abundance such as to give the local abundance we measure today.

The DM accretion process onto NSs has been previously estimated [17] by means of the DM particle capture rate,  $C_\chi$ , given an equation of state for regular standard-model matter in the interior of the NS at a given galactic location and with a corresponding ambient DM density. Taking as reference a local value for DM density  $\rho_{\chi,0}^{\text{ambient}} \simeq 0.3 \text{ GeV/cm}^3$ , the DM capture rate is approximated as

$$C_\chi \simeq 3.25 \times 10^{22} \left( \frac{1 \text{ TeV}}{m_\chi} \right) \left( \frac{\rho_\chi^{\text{ambient}}}{0.3 \text{ GeV/cm}^3} \right) \text{ s}^{-1}. \quad (2)$$

Therefore, in the NS, the DM particle number,  $N_\chi$ , can be written through a differential equation considering competing processes, namely DM capture and decay, the latter via a generic decay rate  $\Gamma$  as

$$\frac{dN_\chi}{dt} = C_\chi - \Gamma N_\chi, \quad (3)$$

resulting in a DM population at time  $t$

$$N_\chi(t) = \frac{C_\chi}{\Gamma} + \left( N_\chi(t_{\text{col}}) - \frac{C_\chi}{\Gamma} \right) e^{-\Gamma(t-t_{\text{col}})}, \quad t > t_{\text{col}}. \quad (4)$$

The solution takes into account the possibility of an existing DM distribution in the progenitor star before the time of the collapse,  $t_{\text{col}}$ , producing the supernova explosion.

Depending on the  $\chi$ -mass and thermodynamical conditions inside the star, it may be possible to thermally stabilize a DM internal distribution. In this case the DM particle density takes the form

$$n_\chi(r, T) = \frac{\rho_\chi}{m_\chi} = n_{0,\chi} e^{-\frac{m_\chi}{k_B T} \Phi(r)}, \quad (5)$$

with  $n_{0,\chi}$  the DM particle density at the NS center.  $\Phi(r)$  is the gravitational potential  $\Phi(r) = \int_0^r \frac{GM(r')dr'}{r'^2}$ . Assuming a constant baryonic density in the core  $M(r) = \int_0^r \rho_n 4\pi r'^2 dr'$ . Finally we obtain

$$n_\chi(r, T) = n_{0,\chi} e^{-(r/r_{\text{th}})^2}, \quad (6)$$

with a thermal radius  $r_{\text{th}} = \left( \frac{3kT}{2\pi G \rho_n m_\chi} \right)^{1/2}$ .

The progenitor star may indeed have accumulated enough DM at the time the supernova explodes. In order to estimate this amount, we will consider a  $15M_\odot$  progenitor. After the He burning stage for  $t_{\text{He} \rightarrow \text{CO}} \simeq 2 \times 10^6 \text{ yr}$  a CO mass  $\sim 2.4M_\odot$  sits in the core with a radius  $R \sim 10^8 \text{ cm}$ . The gravitationally captured DM population is  $C_\chi^{\text{He} \rightarrow \text{CO}} t_{\text{He} \rightarrow \text{CO}} \simeq 3.35 \times 10^{39} \left( \frac{1 \text{ TeV}}{m_\chi} \right) \left( \frac{\rho_\chi^{\text{ambient}}}{0.3 \text{ GeV/cm}^3} \right)$  particles. In this case, a coherence factor relates the nucleus (N) and nucleon (n) scatterings, i.e.  $\sigma_{\chi N} \simeq$

$A^2 \left( \frac{\mu}{m_n} \right)^2 \sigma_{\chi n}$  where  $A$  is the baryonic number and  $\mu$  the reduced mass for the  $\chi - N$  system. Since the later stages proceed rapidly, this expression gives the main contribution to the progenitor. As the fusion reactions happen at higher densities and temperatures, the DM thermal radius contracts. In this way, for example, for  $m_\chi = 1 \text{ TeV}$  in the  $\text{He} \rightarrow \text{CO}$ ,  $r_{\text{th}} \simeq 470 \text{ km}$ , while for  $\text{Si} \rightarrow \text{FeNi}$ ,  $r_{\text{th}} \simeq 70 \text{ km}$ . The thermalization time  $t_{\text{th}}$  is accordingly small

$$t_{\text{th}}^{-1} = \left( \frac{3k_B T}{m_\chi} \right)^{1/2} \frac{\sigma_{\chi N} n_N m_\chi m_N}{(m_\chi + m_N)^2} \quad (7)$$

where  $n_N = \frac{\rho_N}{m_N}$ . For the two cases mentioned above, both are small compared to the dynamical time  $t_{\text{th}}/t_{\text{He} \rightarrow \text{CO}} \simeq 10^{-5}$ ,  $t_{\text{th}}/t_{\text{Si} \rightarrow \text{FeNi}} \simeq 10^{-7}$ . However during the core collapse, the dynamical timescale involved is  $\Delta t_{\text{dyn col}} \simeq \sqrt{\frac{3}{8\pi \bar{\rho} G}} \simeq 10^{-3} \text{ s}$  where  $\bar{\rho}$  is an average matter density. Assuming a proto-NS forms with  $T \simeq 10 \text{ MeV}$ , central density  $n_n = 5n_0$  and a neutron-rich fraction  $Y_{\text{neut}} \sim 0.9 - 1$ ,  $n_{\text{neut}} = Y_{\text{neut}} 5n_0 \simeq \frac{p_{\text{F,neut}}^3}{3\pi^2}$ , thermalization time in this phase takes longer to be achieved [18]  $t_{\text{th}} = \left( \frac{2m_\chi^2}{9m_n k_B T} \frac{p_{\text{F,neut}}}{mn} \frac{1}{n_n \sigma_{\chi n}} \right) \simeq 10^{-2} \text{ s}$ .

The core collapse may thus affect the DM population inside the star as just a fraction will be gravitationally retained. Due to the lack of gravitational binding and possibly high initial velocity kicks, the remaining DM particles outside the proto-NS may evaporate. The number of DM particles in the star interior,  $r < R_*$ , is written as  $N_\chi = \int_0^{R_*} n_{0,\chi} e^{-(r/r_{\text{th}})^2} dV$ . It is a dynamical quantity since  $r_{\text{th}}$  is temperature (time) dependent. As long as  $R_* \gg r_{\text{th}}$ , we obtain  $N_\chi = n_{0,\chi} (\pi r_{\text{th}})^3$ . The retained fraction is

$$f_\chi = N_\chi^{-1} \int_0^{R_{\text{PNS}}} n_{0,\chi} e^{-(r/r_{\text{th}})^2} dV, \quad (8)$$

so that for a  $R_{\text{PNS}} \simeq 10 \text{ km}$ ,  $f_\chi \simeq 2 \times 10^{-3}$ . The retained DM population in the PNS after the collapse is thus  $N_\chi = N_\chi(t_{\text{col}}) f_\chi \simeq 6.7 \times 10^{36} \left( \frac{f_\chi}{2 \times 10^{-3}} \right) \left( \frac{1 \text{ TeV}}{m_\chi} \right)$ . Let us note that the central DM density in the newly formed PNS  $n_{0,\chi} \simeq 3 \times 10^{23} \text{ cm}^{-3}$  is much smaller than that in the baryonic medium  $\sim 10^{38} \text{ cm}^{-3}$ . Although rare, and in a similar way to proton decay experiments, we can estimate the number of DM decays in the NS phase within a time interval  $\Delta t = t - t_{\text{col}} \ll \Gamma^{-1}$  using a linear approximation in Eq. (4) and with aid of Eq. (8),

$$N_{D,\chi} = N_\chi(t_{\text{col}}) f_\chi \Gamma \Delta t. \quad (9)$$

For a time interval comparable to known ages of ancient pulsars (like that estimated for the isolated pulsar PSR J0108-1431)  $\Delta t \simeq \tau_{\text{old NS}} = 2 \times 10^8 \text{ yr}$  decays may have profound implications. Neglecting any phase space blocking effects, the number of decays assuming

decay times similar to those in cosmic positron/electron anomaly  $\tau_{e^+e^-}$ , is given by

$$N_{D,\chi} = 4.2 \times 10^{26} \left( \frac{f_\chi}{2 \times 10^{-3}} \right) \left( \frac{1 \text{ TeV}}{m_\chi} \right) \left( \frac{10^{26} \text{ s}}{\tau_{e^+e^-}} \right) \left( \frac{\Delta t}{\tau_{\text{old NS}}} \right), \quad (10)$$

and the time-averaged rate of decays in this case is  $\dot{N}_{D,\chi} = 6.7 \times 10^{10} \left( \frac{f_\chi}{2 \times 10^{-3}} \right) \left( \frac{1 \text{ TeV}}{m_\chi} \right) \left( \frac{10^{26} \text{ s}}{\tau_{e^+e^-}} \right) \text{ s}^{-1}$ .

At this point, we should check that the DM population number indeed does not exceed the Chandrasekar limiting mass for the star to survive. If this was the case, it may lead to gravitational collapse of the star (see [19, 20]). Therefore, for fermionic DM, we expect  $N_\chi(t) < N_{\text{Ch}}$ , where  $N_{\text{Ch}} \sim (M_{\text{Pl}}/m_\chi)^3 \sim 1.8 \times 10^{54} (1 \text{ TeV}/m_\chi)^3$  with  $M_{\text{Pl}}$  the Planck mass, and for the bosonic case  $N_{\text{Ch}} \sim (M_{\text{Pl}}/m_\chi)^2 \sim 1.5 \times 10^{32} (1 \text{ TeV}/m_\chi)^2$ . In case a Bose-Einstein condensate is considered [21]  $N_{\text{BEC}} \simeq 10^{36} (T/10^5 \text{ K})^5$  and the condition is  $N_\chi(t) < N_{\text{Ch}} + N_{\text{BEC}}$ . As described, in the fermionic case, DM remains at all times below the limiting mass, but this may not be the case in the cooling path of the PNS if a Bose-Einstein condensate is formed for a DM particle in the  $\sim \text{TeV}$  mass range. We can see that the scenario described here may be at the border of the collapse case, however we will restrict our discussion to the precollapsed state, leaving the possibility of additional complexity for further investigation.

If we now focus on the typical decay final states of interest for fermionic or bosonic (neutral) DM, we can estimate the energy deposition in the medium. Strictly speaking, injection and deposition are related by an injection fraction that remains unknown since we do not know the preferred decay channels. In this work and in order to size of the effect, we will consider the photon contribution to decays by two-body channels with intermediate (massive) state daughter particles, quarks, leptons, weak bosons  $\Phi_w$  or, more generic  $\Phi$  bosons and photons. Reactions include  $\chi \rightarrow \Phi_w \Phi_w, l^+ l^-, q^+ q^-, 2\Phi, \Phi \gamma, \chi \rightarrow \Phi_w l$ , keeping in mind more generic decay final states [22] may well happen. Using the photon spectrum  $\frac{dN_\gamma}{dE}$  from [23, 24], we estimate the rate of particles injected per unit volume and unit energy in the  $i$ th-channel with corresponding decay rate  $\Gamma_i$  at stellar radial location  $r$

$$Q(E, r) = n_\chi(r) \sum_i \Gamma_i \frac{dN_\gamma^i}{dE}. \quad (11)$$

Then the energy rate injected in the prompt decay channel is written as

$$\frac{dE}{dt} = \int \int EQ(E, r) dE dV \quad (12)$$

Energy release from DM decay is injected in a typical volume  $V_{\text{th}} = \frac{4}{3} \pi r_{\text{th}}^3$ , where heating and cooling processes compete. At this point we must note that although there are indeed energy losses due to photon cooling and gravitational contraction, these effects do not significantly

change the picture. As a result, over a time interval  $\Delta t < \tau_{\text{old NS}}$  the DM decay has a local net heating effect yielding an additional average energy density

$$u_{\text{decay}} \simeq \Delta t \int \int EQ(E, r) dE dV. \quad (13)$$

DM decay may be regarded as a spark-seeding mechanism in similar fashion to modern versions of other nucleation experiments such as COUPP [25] based on *hot spike* models. In the present case this may allow further changes induced in the NS as a result of possible quark bubble nucleation. A thermally induced quark bubble nucleation, has been already suggested [26] and some studies [27] conclude that quark matter bubbles may nucleate if the temperature exceeds a few MeV, provided the MIT model bag constant is  $B^{1/4} = 150 \pm 5 \text{ MeV}$ . In the scenario depicted here, the energy release in decays may provide the injection of energy to create a bubble. In order to see this we estimate the minimum critical work needed to nucleate a neutral stable spherical quark bubble in the core of the cold NS. It is given by [27]

$$W_c = \frac{16\pi}{3} \sqrt{\frac{2\gamma^3}{\Delta P}}, \quad (14)$$

where  $\Delta P = P_q - P_n$  is the pressure difference and  $P_q$  ( $P_n$ ) is the quark (nucleon) pressure. For a two-flavour ud-quark system this is given by  $P_{ud} = \sum_{i=u,d} \frac{\mu_i^4}{4\pi^2} - B$

and assuming a neutron-rich system  $P_n \simeq \frac{\mu_n^2 - m_n^2}{15\pi^2 m_n}$  and all pressure will effectively be provided by neutrons.  $\gamma = \sum_{i=u,d} \frac{\mu_i^2}{8\pi^2}$ , is the curvature coefficient and  $\mu_i$  ( $\mu_n$ )

is the quark (nucleon) chemical potential related to the Fermi momentum of the degenerate system  $\mu_i = p_{Fi}$  ( $\mu_n = \sqrt{m_n^2 + p_{Fn}^2}$ ). Electrical charge neutrality requires for the ud matter  $n_d = 2n_u$  and  $n_n = \frac{n_u + n_d}{3}$  with  $n_i = \frac{\mu_i^3}{\pi^2}$  in the light quark massless limit. Note that we do not include further refinements due to quark masses, in-medium effects, Coulomb or surface droplet tension since they do not change the global picture as we want to keep a compact meaningful description of the nucleation process. Bubbles have a radius  $R_c = \sqrt{2\gamma/\Delta P}$  and their stability is granted as they reach the minimum baryonic number  $A_{\text{min}} \sim 10$  when  $A \sim R_c^3 n_n > A_{\text{min}}$ .

The energy density necessary to create a quark bubble with volume  $V_d \simeq \frac{4}{3} \pi R_c^3$  is therefore  $u_{\text{bub}} \simeq W_c/V_d \simeq 5.4 \times 10^{35} \text{ erg/cm}^3$ . This estimate is in agreement with similar and more detailed calculations [28]. Then to allow the quark bubbles to nucleate, the average energy densities must be of the same order, i.e.,  $u_{\text{decay}} \gtrsim u_{\text{bub}}$ . For a cold and old NS, the central temperature is  $T \sim 10^5 \text{ K}$  and if a quark deconfinement transition in a bubble size comparable to the DM thermal volume takes place, it most likely will produce a macroscopic transition. Some attempts to model this computationally have been recently performed in [29].

In Fig (1), we can see the logarithm of the DM particle decay time versus its mass. The colored regions represent exclusion regions for the decaying particle phase space since they would produce NS transitions over ages below those assumed for regular NS. Darker colored regions represent more efficient energy deposit processes, corresponding gradually to bosonic (fermionic) decay channels for more (less) efficient energy injection. Data points correspond to the required lifetimes from [5] and [11]. Since NS can effectively test decaying DM, there is thus a natural scale constrained by its lifetime  $\tau_{\text{old NS}}$ . We can thus use this result to set exclusion regions for  $\tau_\chi$  complementary to those shown in other works [4][11][10][6].

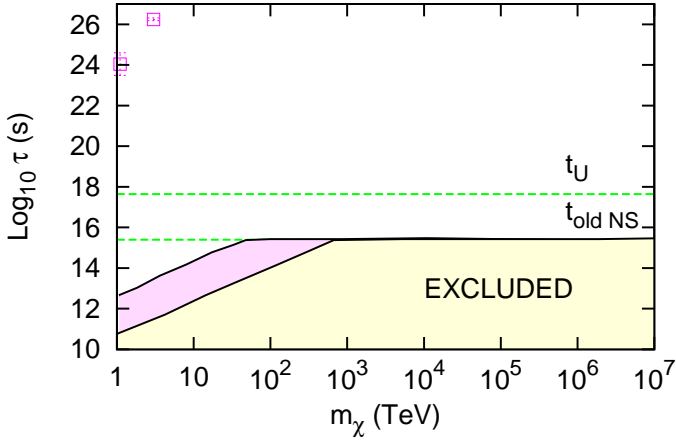


FIG. 1. Logarithm of DM decay time as a function of mass. Colored regions signal injection efficient channels where NS deconfinement transition may take place.  $\rho_{\chi,0}^{\text{ambient}} \simeq 0.3 \text{ GeV/cm}^3$ . Data points refer to fits [5] [11] obtained from cosmic electron/positron asymmetry. Universe and old NS ages are plotted with dashed lines.

We can see that for  $\tau_\chi \lesssim 6.3 \times 10^{15} \text{ s}$ , masses  $(m_\chi/\text{TeV}) \gtrsim 8 \times 10^2$  are excluded. Since the bubble nucleation may involve complex dynamics, we do not attempt to model the details here and we estimate that the number of bubbles being created by spark seeding due to DM decay is given by  $\dot{N}_{\text{bub}} \simeq \frac{dN_{\text{bub}}}{dE} \frac{dE}{dt}$ , and over NS lifetime  $N_{\text{bub}} \simeq \dot{N}_{\text{bub}} t$ . If this was indeed the scenario, a possible catastrophic event of NS to quark star transition could happen when the macroscopic deconfinement proceeds via detonation modes to rapidly consume the star. The GRB signal emitted has been estimated in [15] and subsequent emission in the cosmic ray channels is also expected [16].

In our galaxy, the supernova rate is about  $R = 10^{-2} \text{ yr}^{-1}$  so that an average rate of NS formation over the age of the universe  $\tau_U \sim 4.34 \times 10^{17} \text{ s}$  yields  $N_{\text{NS}} \sim R\tau_U \sim 10^{8 \div 9}$ . Given this population, one should be able to set a lower limit for  $\tau_\chi$  on the age of the oldest NS known.

In order to further compare with other analyses in the literature, we consider a generic decay process where

a decaying DM particle produces a stable DM (SDM) particle  $\Phi_{\text{SDM}}$  and a lighter particle  $L$  in a reaction  $\chi \rightarrow \Phi_{\text{SDM}} L$ . The mass loss fraction  $f = \frac{m_\chi - m_{\Phi_{\text{SDM}}}}{m_\chi}$  and the recoil kick velocity of the SDM is  $v_k = fc$ , assuming non-relativistic momenta. We assume the lighter particle is injected into the medium. The spectrum in this channel allows us to plot the exclusion phase space as shown in Fig. (2). We depict DM decay time (in Gyr) versus recoil kick velocity (in km/s). Excluded (blue-colored) regions based on previous work by Wang et al. [10] on combined CMB and Ly- $\alpha$  analysis are compared with our constraints (green regions). We assume again ambient  $\chi$ -densities of  $\sim 0.3 \text{ GeV/cm}^3$ . We can see that the low ( $1 \lesssim v_k \lesssim 10$ ) km/s unrestricted region in [10] is effectively constrained since in those cases there would be efficient production of NS transitions over NS lifetimes.

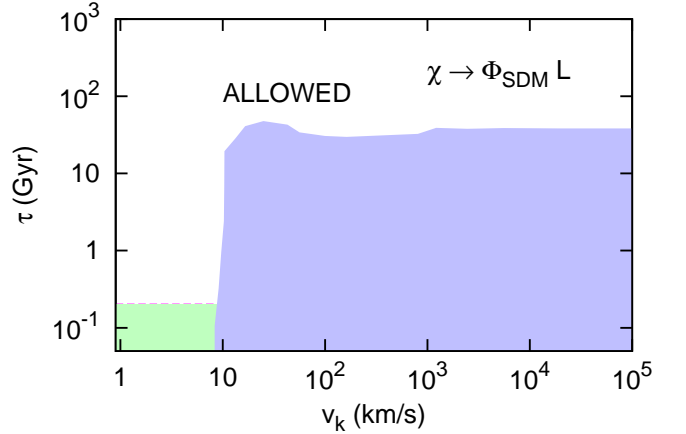


FIG. 2. DM decay lifetime in Gyr as a function of recoil kick velocity in km/s for the  $\chi \rightarrow \Phi_{\text{SDM}} L$  channel. Colored areas represent excluded regions. Blue regions are constraints from combined CMB and Ly- $\alpha$  analysis [10] while green regions are constrained by this work.

In conclusion, we have shown that the current population of NS in the galaxy may have the capability of further constraining the nature of a possibly decaying bosonic or fermionic DM particle with mass in the  $\gtrsim \text{TeV}$  range. In this case, DM particles with lifetimes  $\tau_\chi \lesssim 6.3 \times 10^{15} \text{ s}$  exclude masses  $(m_\chi/\text{TeV}) \gtrsim 5 \times 10^1$  or  $(m_\chi/\text{TeV}) \gtrsim 8 \times 10^2$  in the bosonic or fermionic cases, respectively. These results are obtained from the prior of avoiding nucleation of quark bubbles in a NS core due to efficient energy injection by spark seeding. If this was the case, a conversion from NS into quark star would be triggered, thereby reducing the population of regular NS in the galaxy. Our results provide complementary constraints in the low recoil kick velocity  $v_k$  region of the  $m_\chi - \tau_\chi$  phase space for a weakly interacting DM particle candidate.

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